Experimental Validation of a Coupled Fluid-Multibody Dynamics Model for Tanker Trucks

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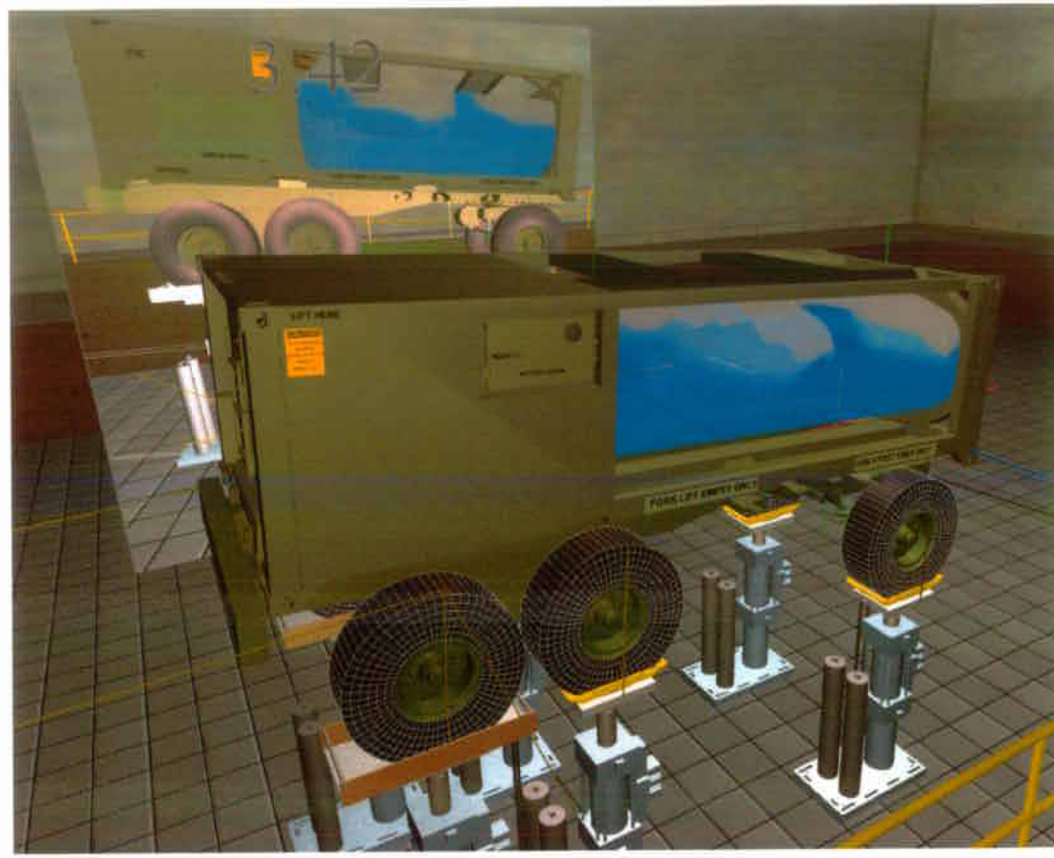
Outline

- Motivation
- Objective
- Literature Review
- FE Formulation
    - Solid
        - Frictional contact model
        - Simple tire model
        - Detailed tire model
    - Fluid
    - Free-surface model
    - Fluid-structure coupling
- Validation Study
- Concluding Remarks



Motivation

- Many practical applications include a flexible multibody system carrying one or more liquid filled tanks:
  - Ground vehicles (truck, train, or car).
  - Ships and sub-marines.
  - Airplanes (commercial or military jet, helicopter, etc.)
  - Space structure (space station or satellite).
  - Sky scrappers earthquake mitigation slosh tanks.
- The tank can be a payload tank or a liquid fuel tank.
- Accurate modeling of the system dynamic response under various operating conditions can help improve: Safety, Reliability, Mobility/Maneuverability, Cost, ...

Objective

- Develop a finite element model for fully-coupled flexible multibody and liquid sloshing. The model must handle the following:
  - Incompressible fluid flow in a moving/deforming container including accurate modeling of:
    - The free-surface.
    - Turbulence.
  - Flexible multibody system modeling, including:
    - Flexible bodies (beams, shells and solids).
    - Rigid bodies.
    - Large arbitrary rigid body rotation.
    - Frictional contact.
    - Joints (spherical, revolute, cylindrical, prismatic).
    - Linear and rotary actuators.
    - Control laws.
  - Coupling between the solid and the fluid at the fluid-structure interface.

Literature Review

Free surface model	Moving / deforming tank model	Fixed grid	ALE	NS written in tank frame	Particles
VOF			Present paper		
Level-set					
ALE					
Particles					

- Approach used in present paper
  - ALE mesh with VOF
    - No cut-cell solid-fluid interface boundary-condition problems.
    - Allows modeling surface break-up and merging without the need for re-meshing.
    - Allows modeling flows in flexible deforming containers.
    - Good fluid mass, momentum and energy conservation.

Finite Element Formulation

- Solid and fluid equations of motion integrated using a time-accurate explicit solution procedure.
- Lumped mass and inertia matrices are used.
- All solid and fluid solution fields are referenced to a global inertial reference frame.

Multibody Dynamics / Solid Mechanics (1/8)

- Semi-discrete dynamic equations of motion:

$$M_K \ddot{x}^t_{Ki} = {F_s}^t_{Ki} + {F_a}^t_{Ki}$$

$$I_{Kij} \ddot{\theta}^t_{Kj} = {T_s}^t_{Ki} + {T_a}^t_{Ki} - \left(\dot{\theta}^t_{Ki} \times (I_{Kij} \dot{\theta}^t_{Kj})\right)_{Ki}$$

- Rotational equations of motion are written in a body (material) frame, with the resulting incremental rotations added to the total body rotation matrix.

Multibody Dynamics / Solid Mechanics (2/8)

- Total Lagrangian – Total displacement formulation.
- Element deformations referenced to the global inertial reference frame.
- Library of truss, beam, and solid nonlinear finite elements with only Cartesian coordinate degrees of freedom allowing arbitrarily large element rotations:
  - Beam element using a torsional spring formulation.
  - Natural-modes eight-node brick elements (No locking or spurious modes) for modeling shells and solids.

Multibody Dynamics / Solid Mechanics (3/8)

- Normal contact modeled using a penalty formulation.

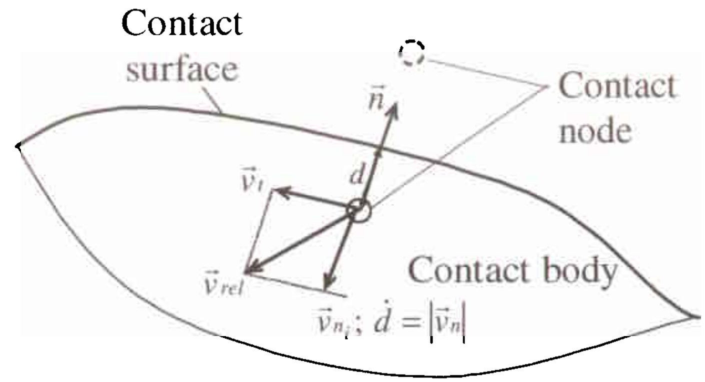
$$F_{normal} = k_p d + \begin{cases} c_p \dot{d} & \dot{d} \geq 0 \\ s_p c_p \dot{d} & \dot{d} < 0 \end{cases}$$

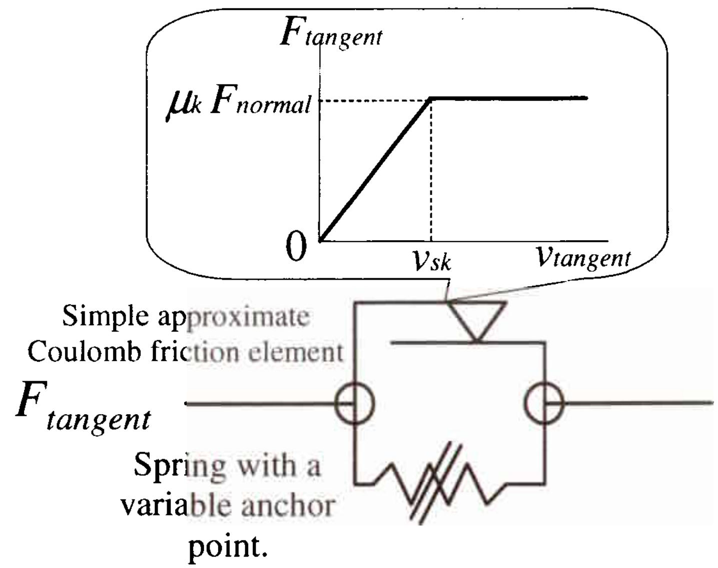
$$F_{node_i} = F_{t_i} + F_{n_i}$$

$$F_{n_i} = n_i F_{normal} \qquad F_{t_i} = F_{tangent} \; t_i$$

- Friction modeled using an accurate and efficient asperity based friction model.

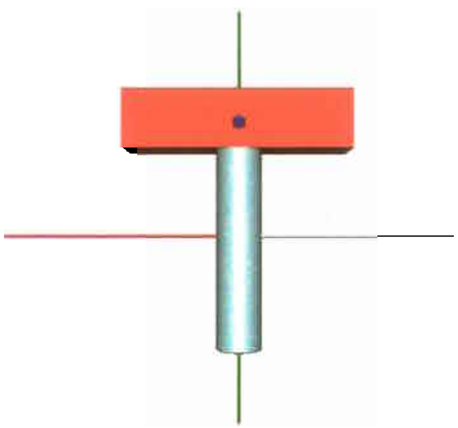
- Binary tree contact search algorithm for fast contact search.
  - Recursively dividing a polygonal surface into 2 blocks of polygons then finding the bounding box for each block of polygons.
  - The contact point is inside a bounding box then the two sub-bounding boxes are checked.



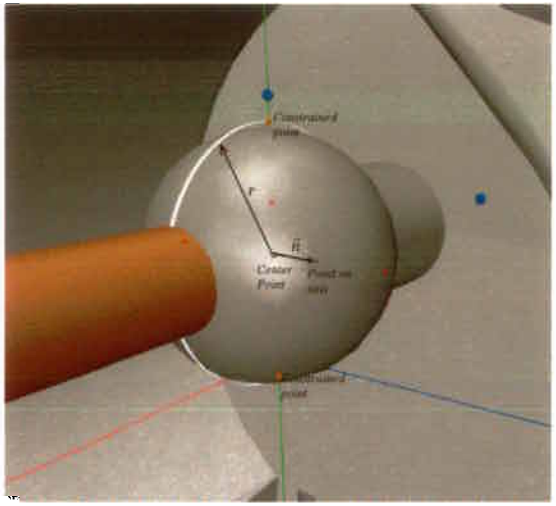


Multibody Dynamics / Solid Mechanics (4/8)

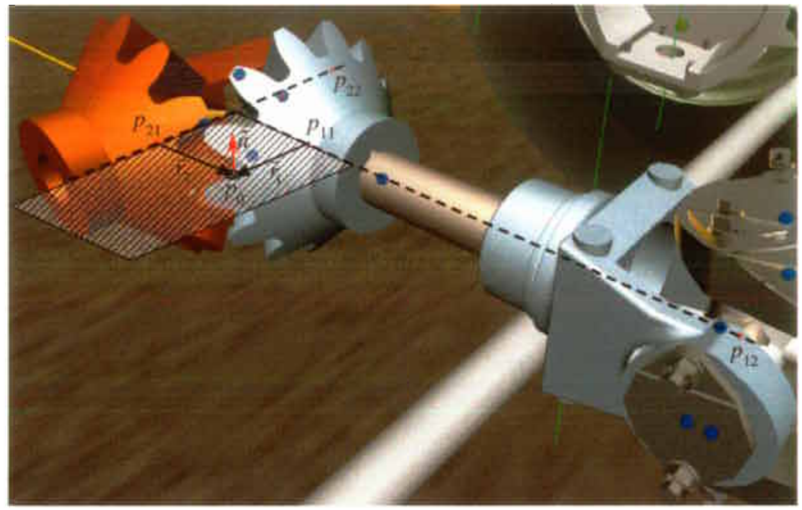
- Penalty formulation for modeling joints (spherical, revolute, cylindrical, prismatic and gear).
- Joint friction modeled using and asperity spring model.



Point joint



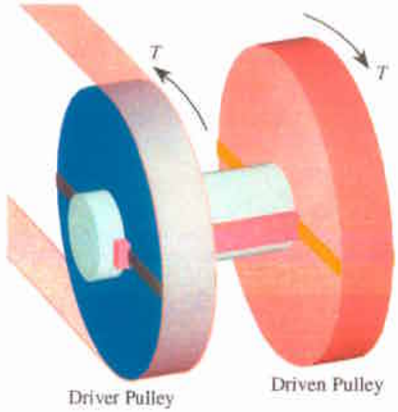
Spherical cylinder joint (CV-Joints)

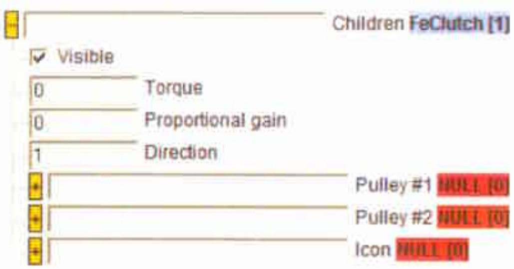


Gear joint

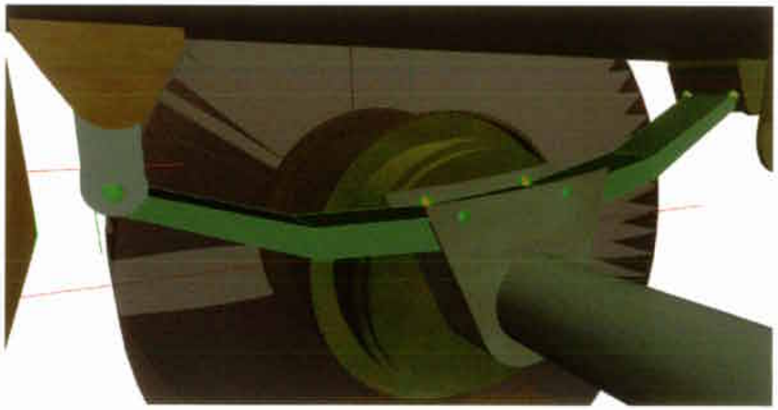
Multibody Dynamics / Solid Mechanics (5/8)

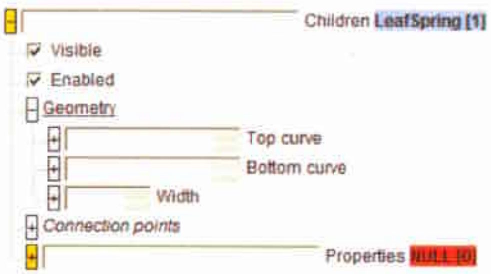
- Elements for modeling clutches and couplers.





- Leaf springs modeled using brick elements with MPCs used to connect the leaf-spring to other bodies .



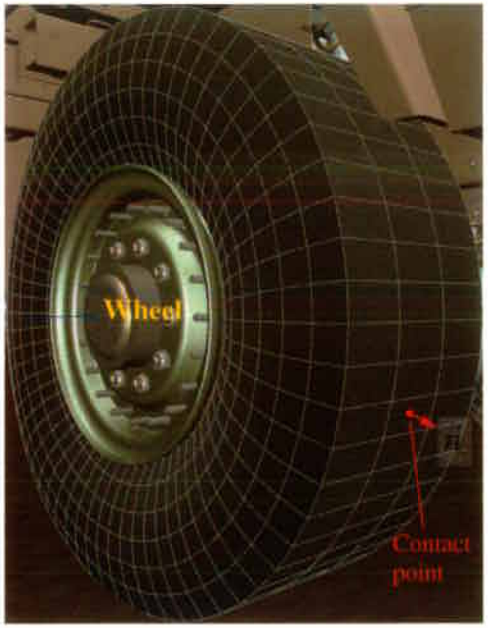


Multibody Dynamics / Solid Mechanics (6/8)

- Simple tire model.
  - A tire is mounted on a rigid body representing the wheel.
  - The tire's external surface is discretized in the circumference and meridian directions into a grid of rectangles with a contact point defined at the center of each rectangle.
  - The contact force at each contact point (sum of the normal contact and tangential friction forces) is transferred as a force and a moment to the center of the wheel.

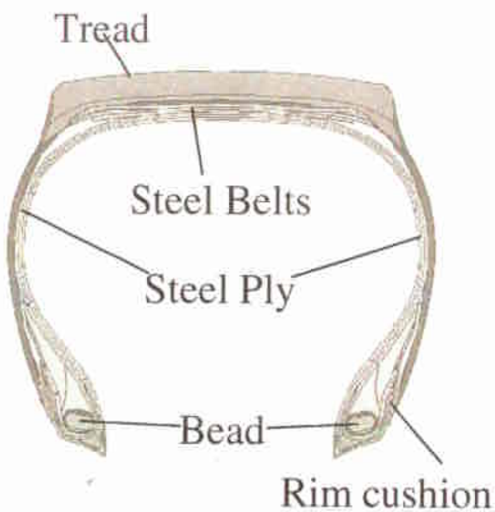
$$x_{Gcp_i} = X_{BF_i} + R_{BF_{ij}}\, x_{Lcp\,j}$$

$$\dot{x}_{Gcp_i} = \dot{X}_{BF_i} + R_{BF_{ij}}\,(W_{BF} \times x_{Lcp})_j$$



Multibody Dynamics / Solid Mechanics (7/8)

- Detailed tire model




Beam reinforcements

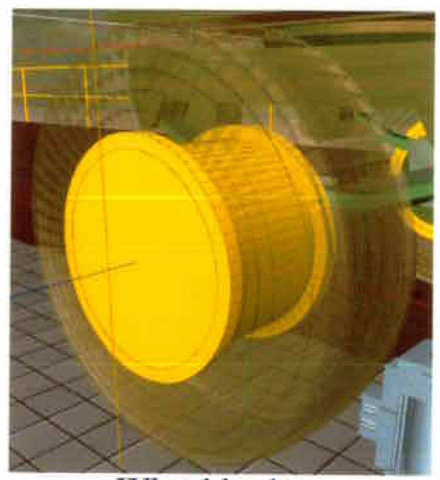

Brick elements


Surface elements

Children

BrickElms_Tire_PLSt_FrontWheelL	Children FeBrickBlock [1]
OuterSurface_Tire_PLSt_FrontWheelL	Children FeBBrickBlock [1]
InnerSurface_Tire_PLSt_FrontWheelL	Children FeBBrickBlock [2]
Rim1Surface_Tire_PLSt_FrontWheelL	Children FeBBrickBlock [1]
Rim2Surface_Tire_PLSt_FrontWheelL	Children FeBBrickBlock [1]
PressureLoad_Tire_PLSt_FrontWheelL	Children FePressureLoad [1]
RimNodes_Tire_PLSt_FrontWheelL	Children NodesCollection [1]
OuterNodes_Tire_PLSt_FrontWheelL	Children NodesCollection [1]
CenterOuterNodes_Tire_PLSt_FrontWhe	Children NodesCollection [1]
ContactRimNodes_Tire_PLSt_FrontWhe	Children FeContactNodes [1]
ContactOuterNodes_Tire_PLSt_FrontWh	Children FeContactNodes [1]
FEtire_bead_Rods_Tire_PLSt_FrontWhe	Children FeTrussBlock [1]
FEtire_ply_Rods_Tire_PLSt_FrontWheel	Children FeTrussBlock [1]
FEtire_belt_Rods_Tire_PLSt_FrontWhee	Children FeTrussBlock [1]
FEtire_MeridianPly_Rods_Tire_PLSt_Fro	Children FeTrussBlock [1]


Contact body


Wheel body

Multibody Dynamics / Solid Mechanics (8/8)

- Characteristics of the modeling technique relevant to modeling ground vehicles.
  - Mass, energy and momentum conservation and virtually no solution drift with time.
  - Accurate prediction of frictional contact behavior for brakes, belts, and tires.
  - Accurate suspension system modeling including asymmetric viscous damping, asymmetric Coulomb friction, and elastic spring.

Fluid Flow Formulation (1/2)

- Time-accurate explicit solution procedure used to solve the semi-discrete Navier-Stokes equations along with the eddy-kinetic energy equation coupled with the solid equations of motion.

Continuity equation

$$\frac{\partial \rho}{\partial t} = \frac{\partial (\rho u c_i)}{\partial x_i}$$

Momentum equation

$$\rho \frac{\partial u_i}{\partial t} = -\rho u c_j \frac{\partial u_i}{\partial x_j} + \frac{\partial \sigma_{ij}}{\partial x_j} + \rho F_i$$

Equation of state

$$\rho = \rho_0 + \beta P$$

Stress equation

$$\sigma_{ij} = -P\,\delta_{ij} + \tau_{ij}$$

Eddy kinetic energy

$$\frac{\partial(\rho K)}{\partial t} = -\frac{\partial(\rho \hat{u}_i K)}{\partial x_i} + \frac{\partial}{\partial x_i}\left[(\mu+\eta)\frac{\partial K}{\partial x_i}\right] + \left(2\eta D_{ij} - \frac{2}{3}\rho K \partial_{ij}\right)\frac{\partial \hat{u}_i}{\partial x_j} - \rho \varepsilon$$

Fluid Flow Formulation (2/2)

- Hexahedral, tetrahedral, and prismatic fluid elements.
- Structured and unstructured grids. All grids are converted internally to an unstructured grid that can include hexahedral, tetrahedral, and/or prismatic elements.
- Incompressible flow using the artificial compressibility technique.
- Finite element and finite volume element formulations. The methods produce very close results.
- ALE formulation for modeling a moving/deforming fluid mesh.
- LES (Large eddy simulation) for modeling turbulence.
- A pressure averaging technique is used to eliminate pressure checker-boarding.
- Streamline upwinding is used to eliminate velocity oscillations for high Reynolds number flows.

Fluid-Structure Model

- Two-way coupling between the multibody system (vehicle) and the fluid is achieved by satisfying the following conditions at the solid-fluid interface:
  - The fluid velocity normal to the solid's surface must be equal to the normal solid velocity.
  - The fluid velocity tangent to the solid surface can range from being equal to the tangential velocity of the solid surface (no slip condition) to being free.
  - No additional energy or momentum to the system should be introduced at the interface.
  - To satisfy the above conditions, a common fluid-solid acceleration is calculated:

$$(m_s + m_f)\dot{\vec{u}}_n = \sum FluidForces + \sum StructureForces$$

$$(m_s + m_f)\dot{\vec{v}}_n = \sum FluidForces + \sum StructureForces$$

$$\left((1-S)m_s + m_f\right)\dot{\vec{u}}_t = (1-S)\sum StructureForces + \sum FluidForces$$

$$\left(m_s + (1-S)m_f\right)\dot{\vec{v}}_t = \sum StructureForces + (1-S)\sum FluidForces$$

Free Surface Model (1/2)

- Acceptor-donor VOF algorithm
  - For each fluid element a VOF value between 0 and 1 is defined.
  - Elements' VOF values are updated each time-step by moving fluid from a completely or partially filled "donor" element to an empty or partially filled neighboring "acceptor" element using:

$$V_{eo} = V_e \ \mathrm{VOF}_e \qquad V_{na} = V_n\,(1 - \mathrm{VOF}_n) \qquad \Delta V = \begin{cases} \Delta t\, S\, A\, \vec{n}.\vec{u} & V_{eo} > \Delta V \ \text{and} \ V_{na} > V_{eo} \\ V_{eo} & V_{eo} < \Delta V \\ V_{na} & V_{na} < \Delta V \end{cases}$$

  - where:
    - *V_e*: element volume
    - *V_n*: neighboring element volume
    - *V_{eo}*: volume of element occupied by the fluid
    - *V_{na}*: volume of the neighboring element available to receive fluid
    - *ΔV*: volume flow through the boundary between the two elements in a time step
    - *Δt*: time step
    - *S*: surface area between the two elements
    - *A*: a value between 0 and 1 indicating the free-surface aperture
    - *n*: unit normal to *S*
    - *u*: fluid velocity vector at the surface *S*.
  - If Δ V<0 then the element is an acceptor element and VOF is not updated (because it will be updated when the neighbor element is set to be the donor element).
  - If Δ V> 0 then the VOF values are updated using:

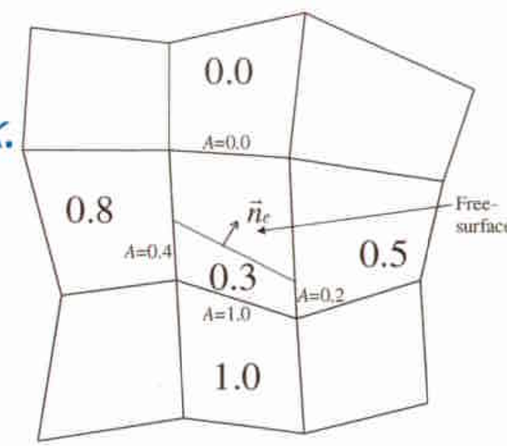
$$\mathrm{VOF}_e = \mathrm{VOF}_e - \Delta V / V_e \qquad \mathrm{VOF}_n = \mathrm{VOF}_n + \Delta V / V_n$$

Free Surface Model (2/2)

- The free-surface apertures A at the element interfaces are used to limit the fluid flow based on the location of the free surface inside the element.
- If VOF=1 then there is no free-surface at the element, therefore A=1.
- If VOF<1 then:
  - Calculate the normal to the surface by looking at a stencil of neighboring elements around the element:

$$n_{e_i} = \mathrm{VOF}_{n_k} S_{n_k} n_{n_{ki}}$$

    where:
    - n_{ei}: ith component of the normal to the free-surface at the element
    - $\mathrm{VOF}n_k$: VOF value for neighboring element number k
    - Sn_k: area of the intersection surface between the element and neighboring element k
    - nn_{ki}: component i of the normal to the surface between the element and neighboring element k.
    - n_e: normalized into a unit vector.
  - Calculate the apertures A for each neighboring element by constructing a planar surface with normal n_e and with total volume equal to $\mathrm{VOF}_e\, V_e$.



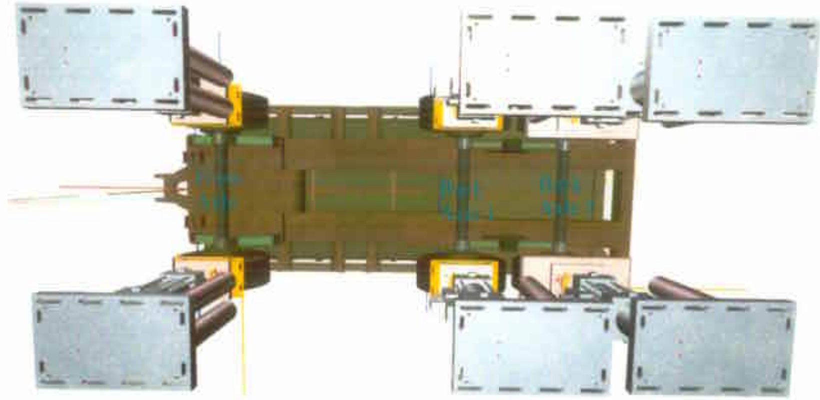
Validation Study

Experiment setup

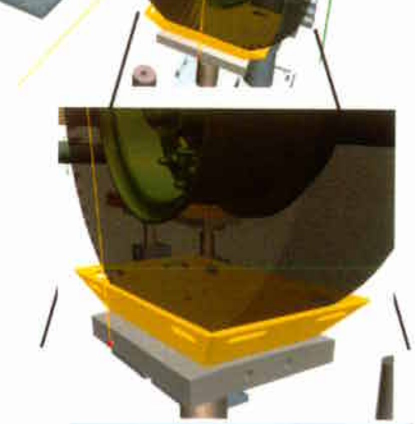
- Full-scale army heavy class tactical PLS (Palletized-Load System) trailer carrying a potable water tank module (Hippo).
- The trailer has 3 axles.
- The trailer is placed on an n-post motion base simulator in TARDEC's Simulation Laboratory (TSL).
- The n-post motion simulator consists of linear hydraulic actuators each placed under one of the trailer's tires.
- Each actuator can be independently commanded to follow a certain vertical displacement time-history.
- The actuators can be controlled in such a way as to simulate vertical position time-histories of the wheels during typical road maneuvers.
- These maneuvers can include: traversing a bumpy terrain, going over symmetric or asymmetric bumps, turning and lane-change.
- Note that the motion simulator cannot simulate the inertial centrifugal and Coriolis forces that arise due to the time-varying motion of the trailer on the road.

Validation Study

Experiment setup (cont.)



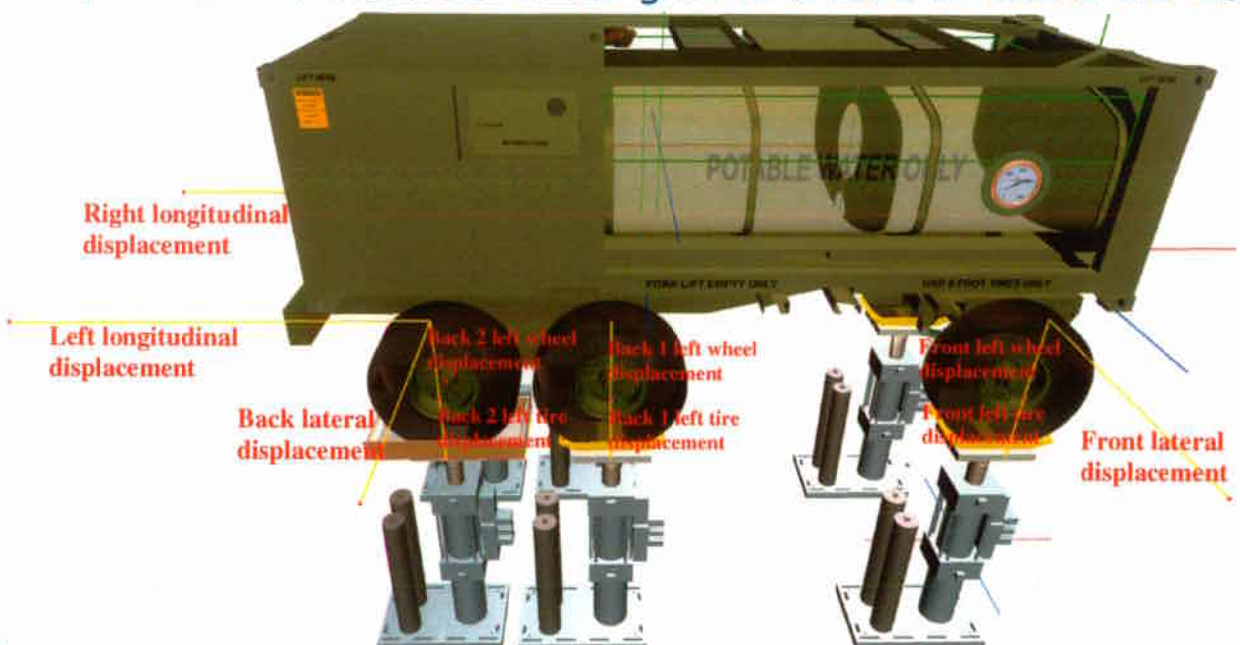
- The trailer in our experimental setup has 3 axles. We call the axles: front axle, back axle 1 and back axle 2.
- Each hydraulic actuator is composed of a cylinder, piston and a dishpan where the tire rests.
- The front and back axle 1 actuators had trapezoidal dishpans for safety reasons to ensure that the trailer does not slide off the motion simulator.
- The two back axle 2 actuators had flat dishpans.
- A wire harness was attached to the top of the trailer at all time during the experiments for safety reasons.



Validation Study

Experiment setup (cont.)

- Displacement data is measured using LVDTs sampled at a rate of 256 samples/sec.
- Displacement is measured at 22 points.
  - Vertical input motion of the 6 actuators (6).
  - Vertical motion of each wheel's center relative to the trailer's frame (6).
  - Vertical deflection of each tire (6).
  - Longitudinal displacements of the trailer's frame relative to ground (2)
  - Lateral displacements of the trailer's frame relative to ground (2).
- 3 acceleration components are measures at the top front center point of the trailer (3).
- A 30 frames/sec camera mounted on the ground is used to record the motion of the trailer.



Validation Study

Test Matrices.

Trailer empty tank experiments (26 experiments).

	Pitch		Roll		Stir	
	Freq. (Hz)	Amp. (mm)	Freq. (Hz)	Amp. (mm)	Freq. (Hz)	Amplitude (mm)
Harmonic excitation	0.7	100	0.5	36	0.5	50
	0.7	140	0.5	48	0.5	70
	1.0	60	1.0	20	0.6	50
	1.0	75	1.0	30	0.6	70
	1.5	20	1.5	5	1.0	30
	1.5	25	1.5	7	1.0	40
	2.0	17	2.0	28		
Ramp excitation	Amp. (mm)		Amplitude (mm)		Amplitude (mm)	
	63 (0.1 sec ramp)		45 (0.1 sec ramp)		155 (0.1sec ramp LF)	
	110(0.2sec ramp)		50 (0.2sec ramp)		110 (0.1sec ramp LB)	

Trailer 65%-filled tank experiments (26 experiments).

	Pitch		Roll		Stir	
	Freq. (Hz)	Amp. (mm)	Freq. (Hz)	Amp. (mm)	Freq. (Hz)	Amp. (mm)
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	0.7	140	0.5	48	0.5	70
	1.0	60	1.0	20	0.6	50
	1.0	75	1.0	30	0.6	70
	1.5	20	1.5	8	1.0	30
	1.5	25	1.5	12	1.0	40
	2.0	17	2.0	30		
Ramp excitation	Amp. (mm)		Amp. (mm)		Amplitude (mm)	
	70 (0.1sec ramp)		50 (0.1 sec ramp)		180 (0.1sec ramp LF)	
	120 (0.2sec ramp)		55 (0.2 sec ramp)		110 (0.1sec ramp LB)	

- Excitations types: Pitch, roll and stir harmonic and ramp.
  - Pitch excitation simulates both sides of the trailer going over a symmetric bump/pothole.
  - Roll motion simulates the trailer turning or going over a bump/pothole only on one side of the trailer.
  - Stir motion simulates a combination of pitch and roll motions.
- For the harmonic excitations the specified amplitude is the peak-to-peak amplitude.
- For the ramp excitations, the amplitude is the difference between the initial value and the final value after the ramp.

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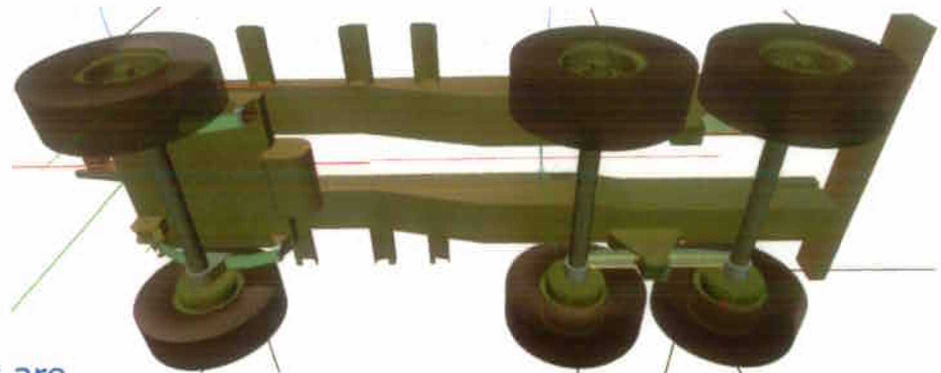
Validation Study

FE Model

- A rigid grounded base.
- Rigid bodies representing the chassis, 3 axles, and suspension system elements.
- 6 linear actuators. The actuator pistons and dishpans are modeled as rigid bodies. Two parallel cylindrical joints are used at each actuator to model a prismatic joint that allows the actuator to move only along the vertical direction.
- 2 front and 2 back leaf-springs modeled using brick elements.
- 6 wheels modeled using rigid bodies. A tire is mounted on each wheel. The tire is in contact with the dishpan of the corresponding actuator piston.
- An oval tank. The tank is modeled as a rigid body. The tank is discretized using 33516 hexahedral fluid elements. The tank has a cross-section baffle near it's center. The baffle has a big round opening at the center and small openings near the bottom and top of the tank to equalize the liquid level.
- Spherical joints are used to model the suspension system connections and the wheels' connections to the axles.



Validation Study

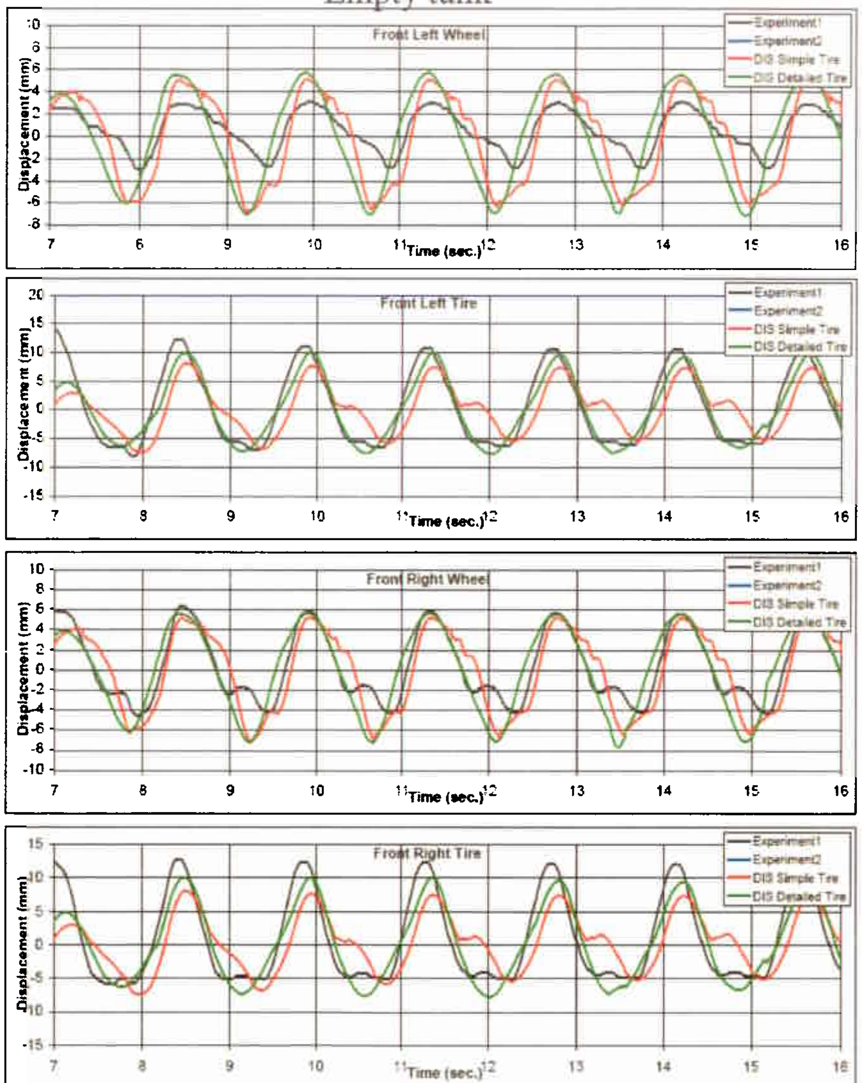
FE Model (cont.)

- Water (ρ = 1000 Kg/m3, μ = 0.001 Kg/m.sec) is modeled as incompressible using the artificial compressibility technique with an artificial sound speed factor of 0.1 (i.e. the artificial sound speed in the water is taken as 1483 m/sec x 0.1 = 148.3 m/sec).
- Full-slip boundary condition at the wall is used. Thus, viscous wall friction effects are assumed to be negligible.
- Gravity is modeled with the gravitational acceleration taken to be 9.8 m/sec^2 in the vertical direction.
- The explicit time step was 1.53×10^{-5} sec.

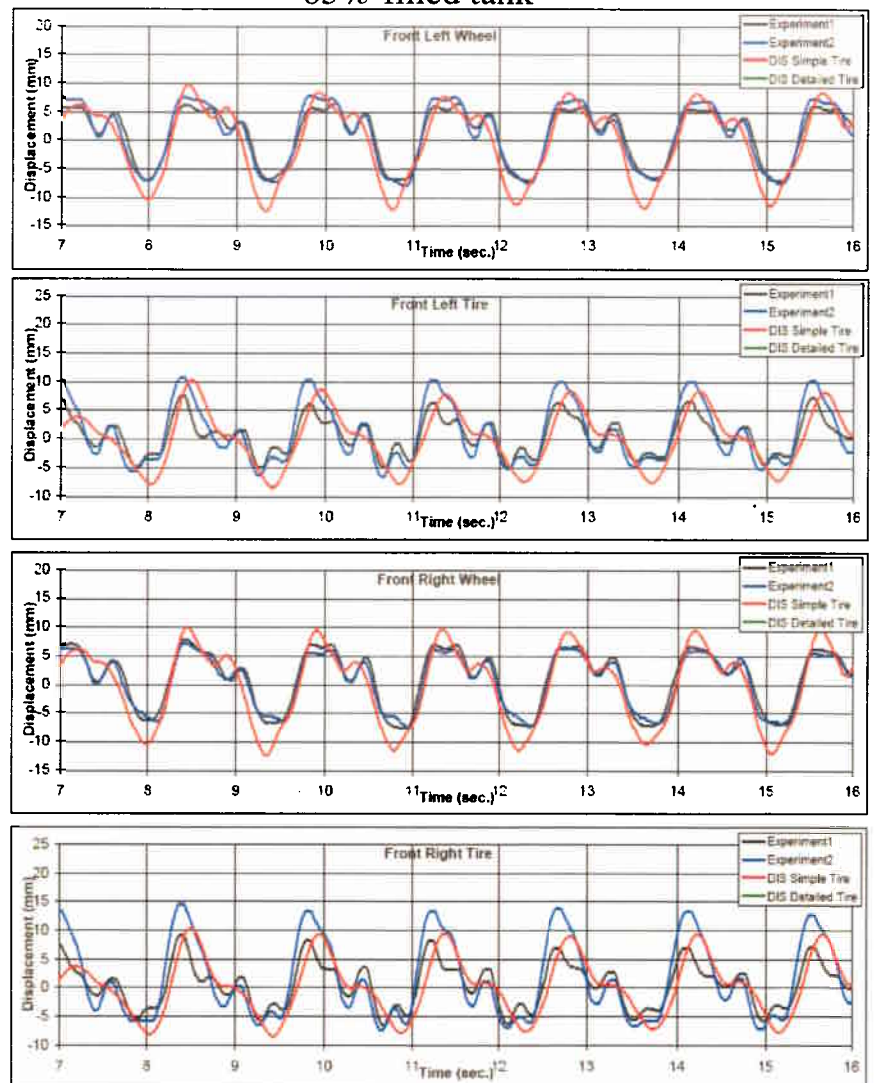
Validation Study

Results: pitch 0.7 Hz; 140 mm harmonic excitation

Empty tank



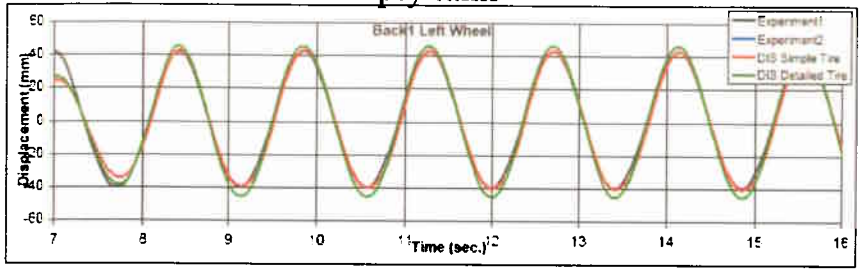
65%-filled tank

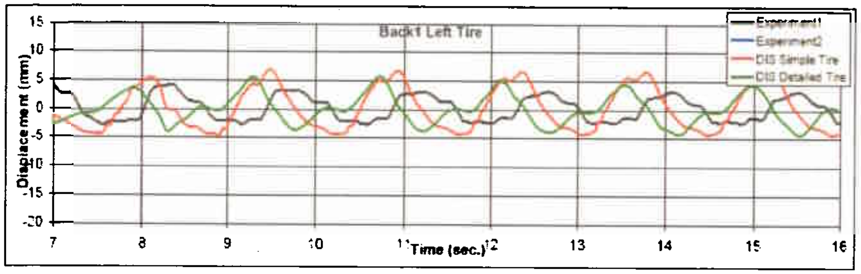


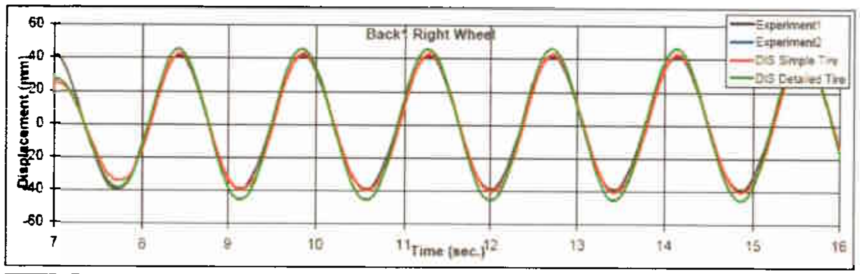
Validation Study

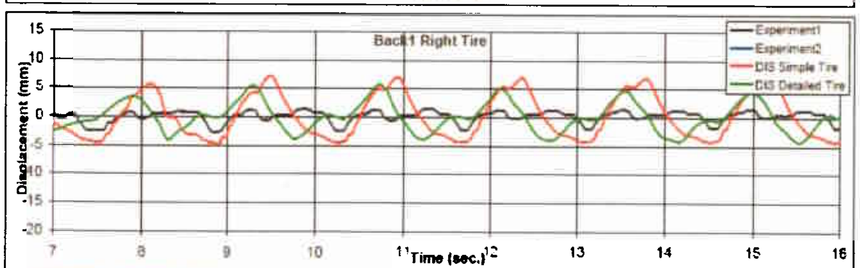
Results: pitch 0.7 Hz; 140 mm harmonic excitation (cont.)

Empty tank

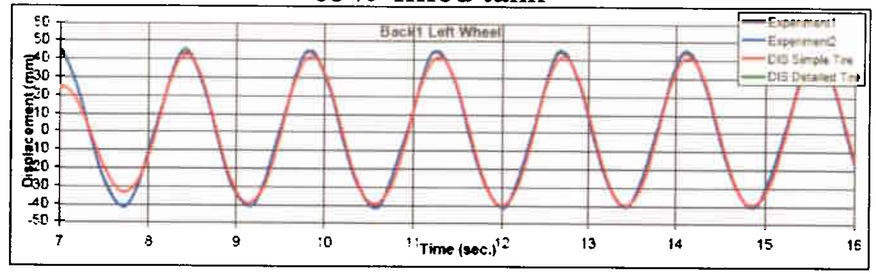


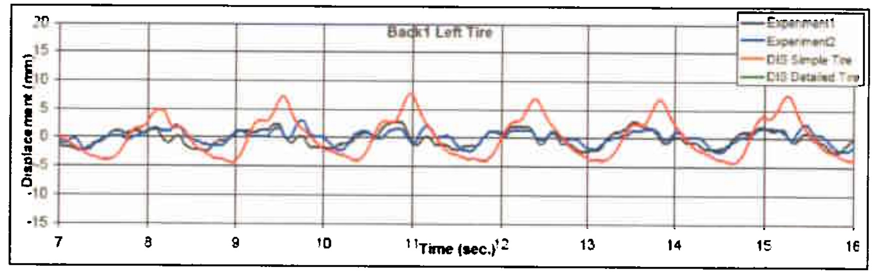


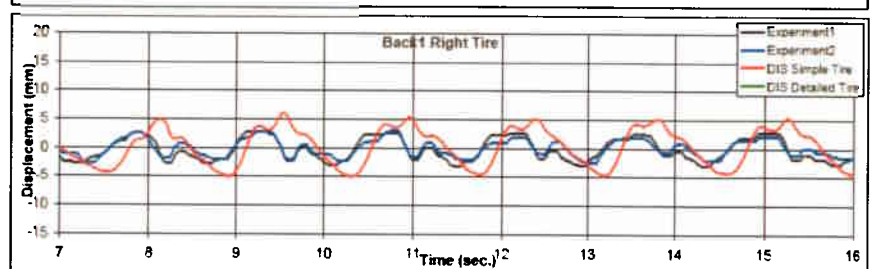




65%-filled tank

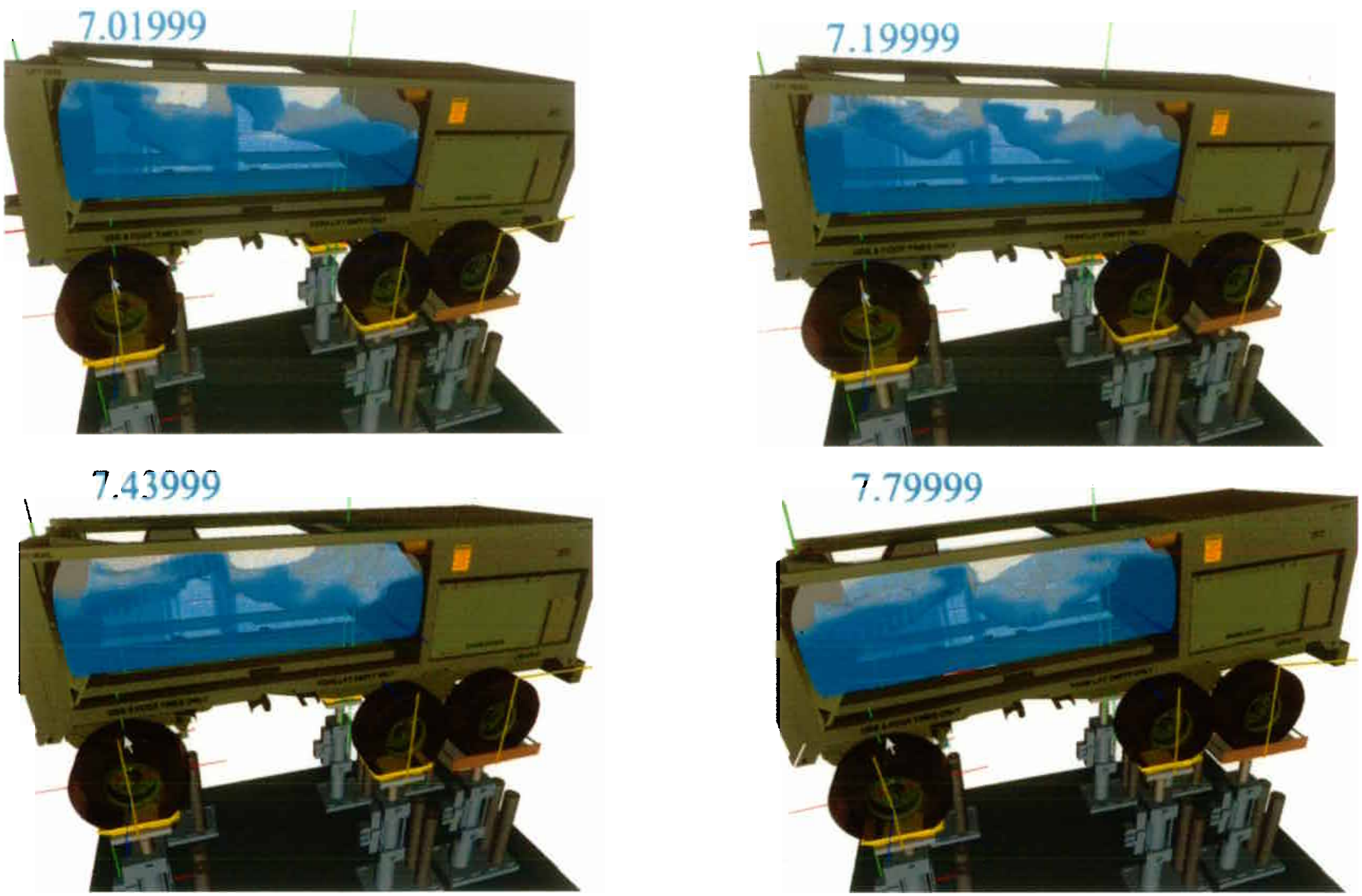






Validation Study

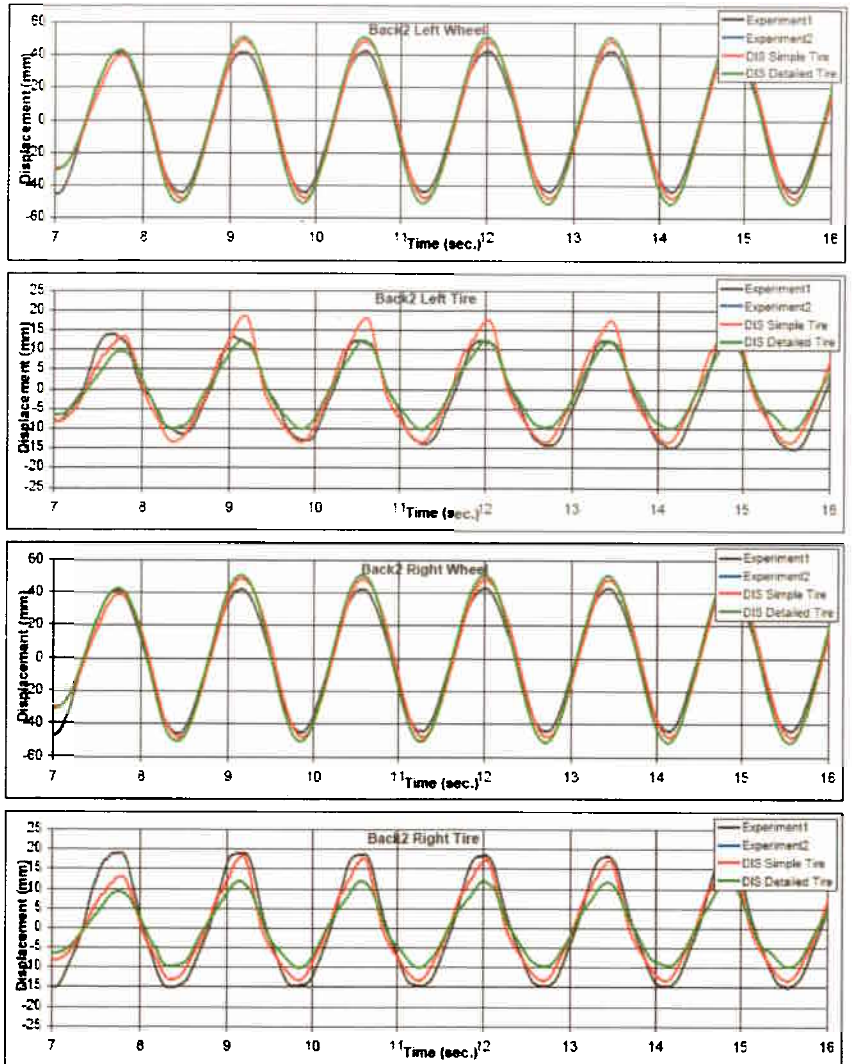
Results: pitch 0.7 Hz; 140 mm harmonic excitation (cont.)



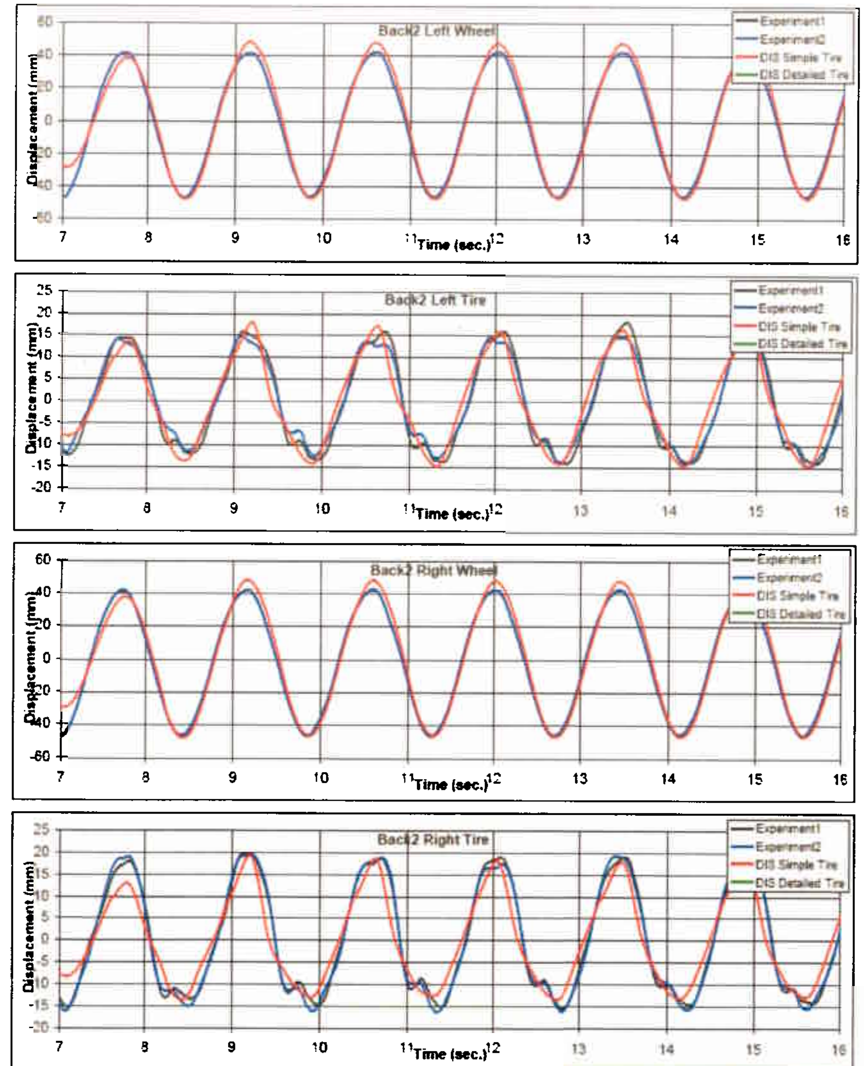
Validation Study

Results: pitch 0.7 Hz; 140 mm harmonic excitation (cont.)

Empty tank



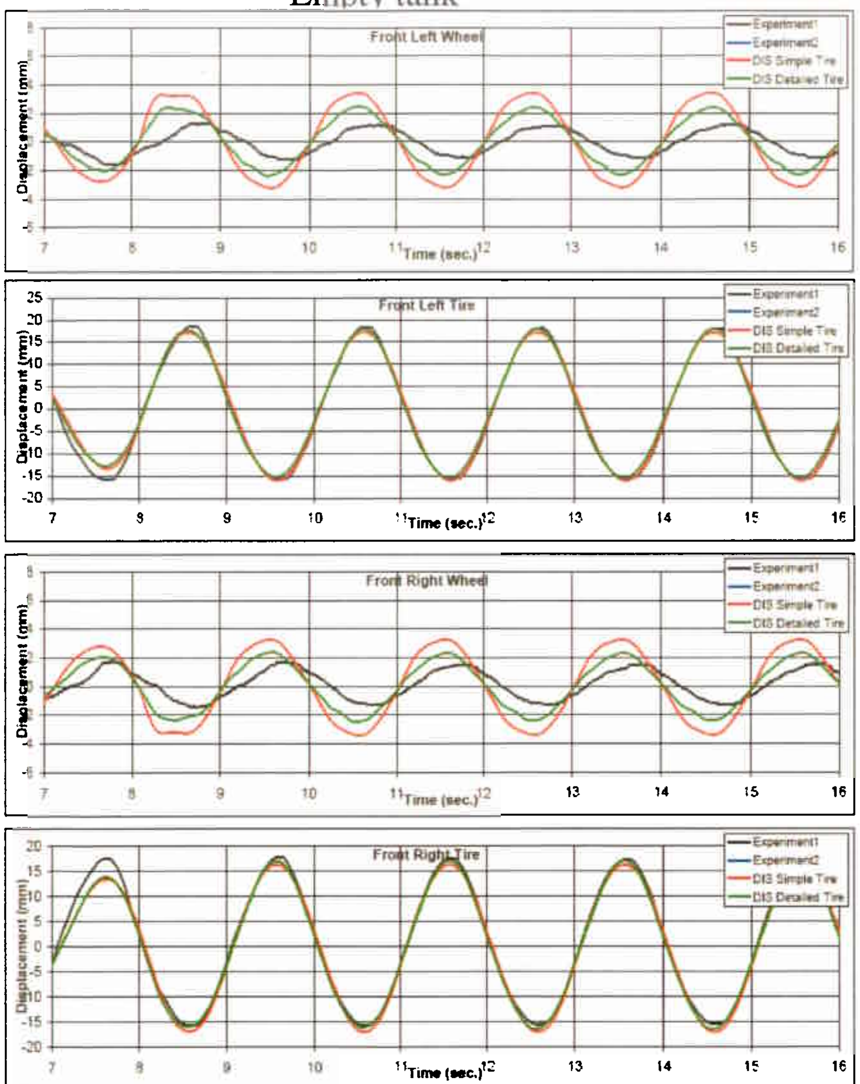
65%-filled tank



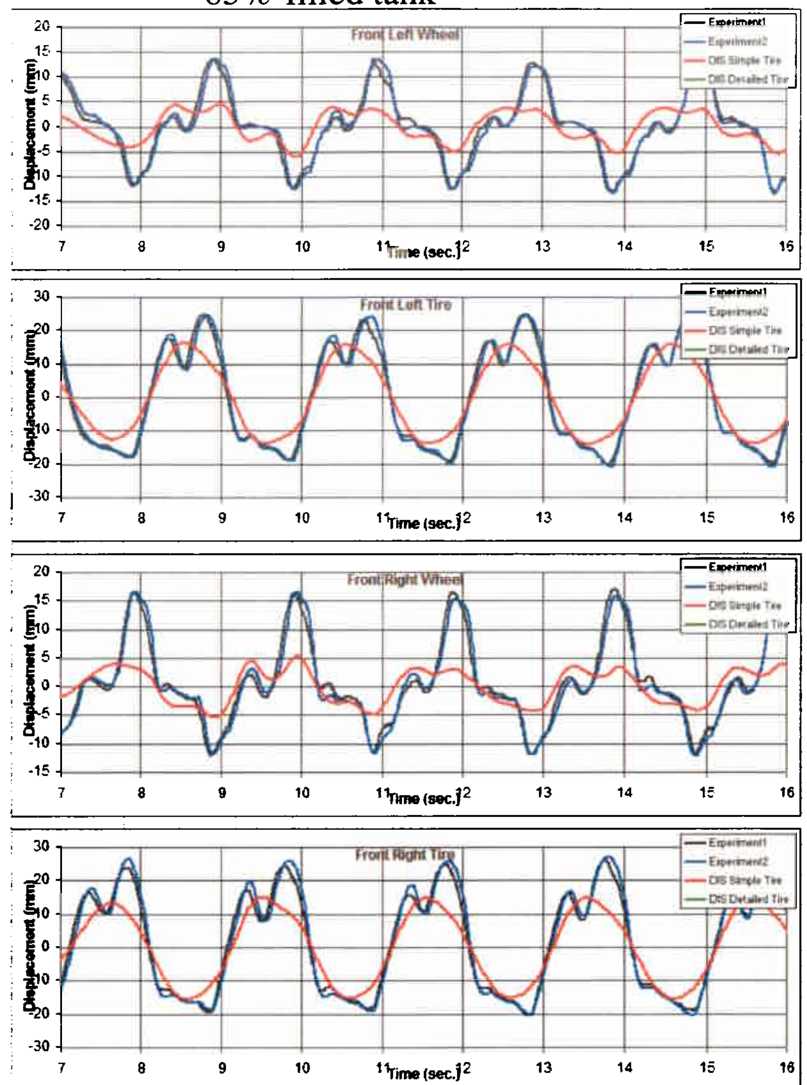
Validation Study

Results: roll 0.5 Hz; 48 mm harmonic excitation

Empty tank



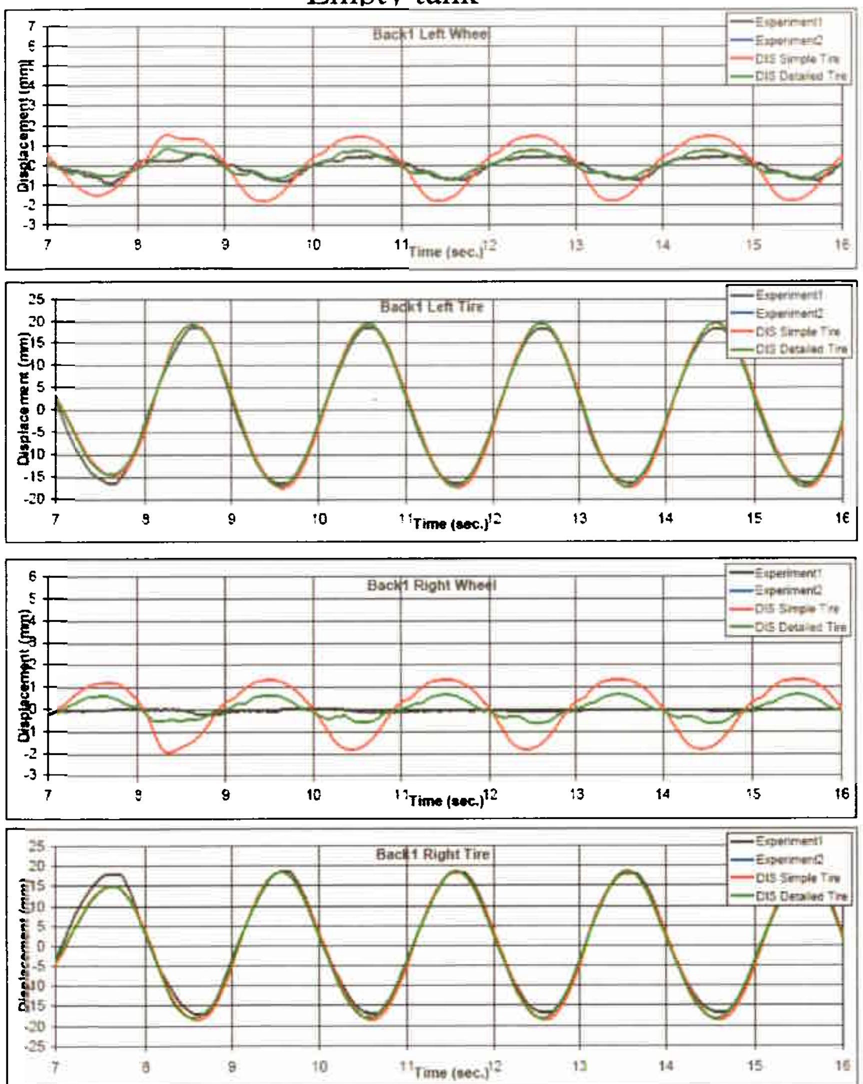
65%-filled tank



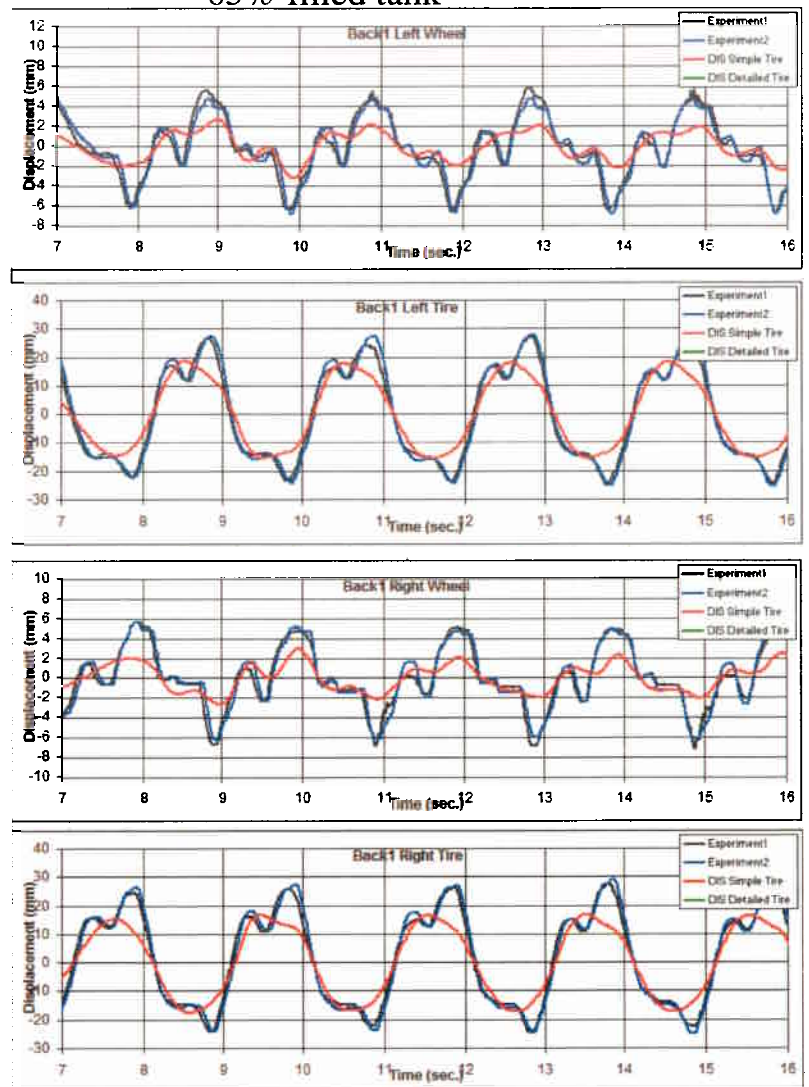
Validation Study

Results: roll 0.5 Hz; 48 mm harmonic excitation (cont.)

Empty tank



65%-filled tank



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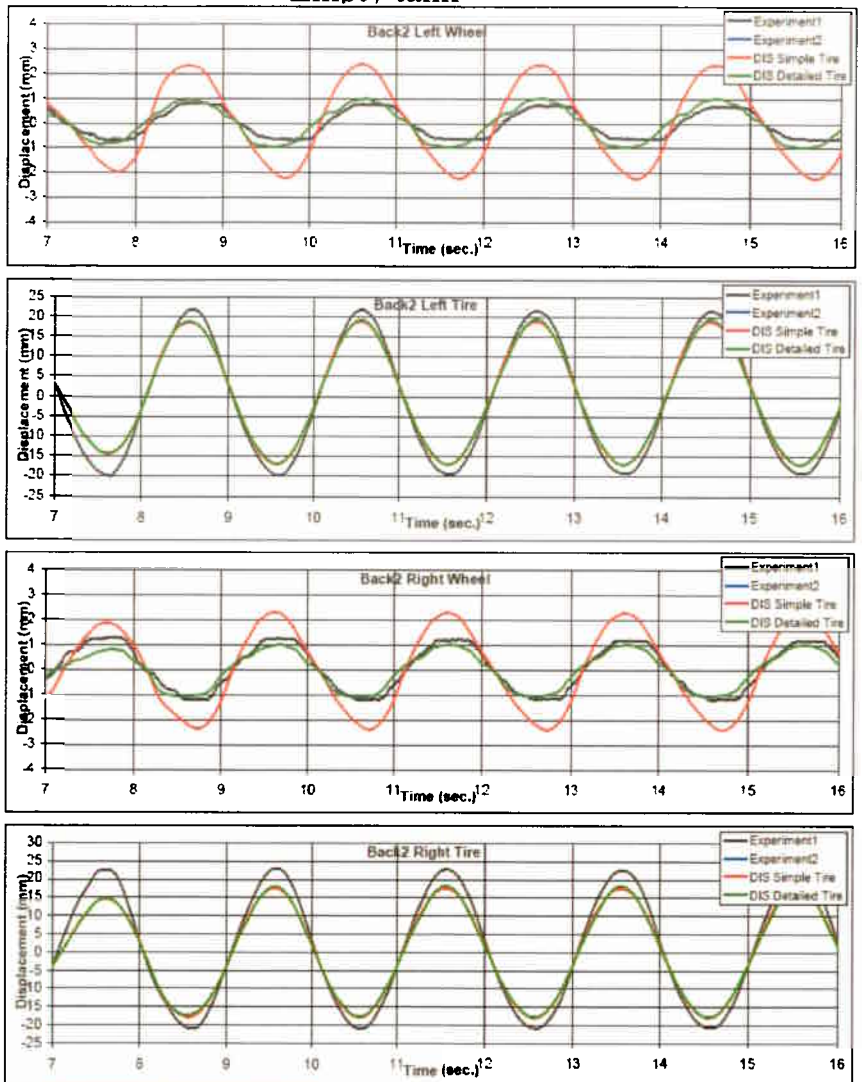
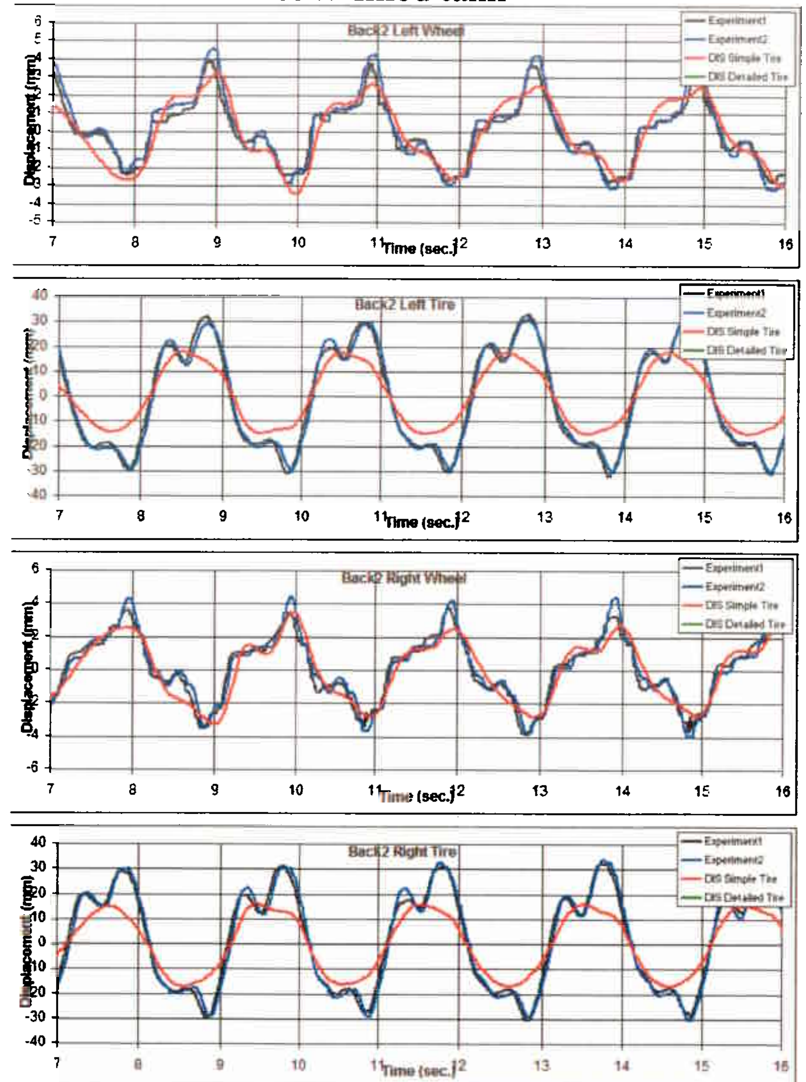
Validation Study

Results: roll 0.5 Hz; 48 mm harmonic excitation (cont.)

Empty tank



65%-filled tank



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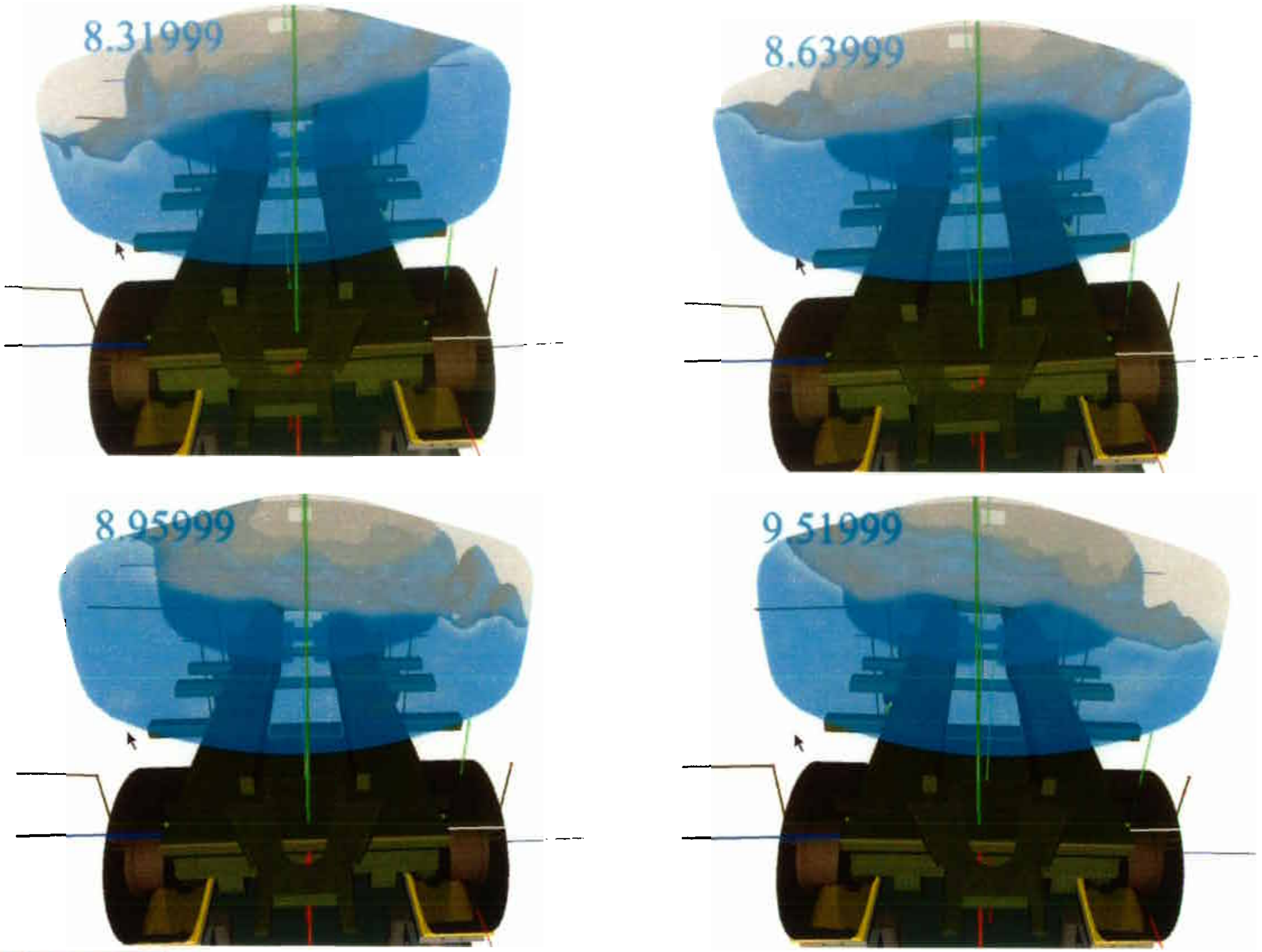
Validation Study

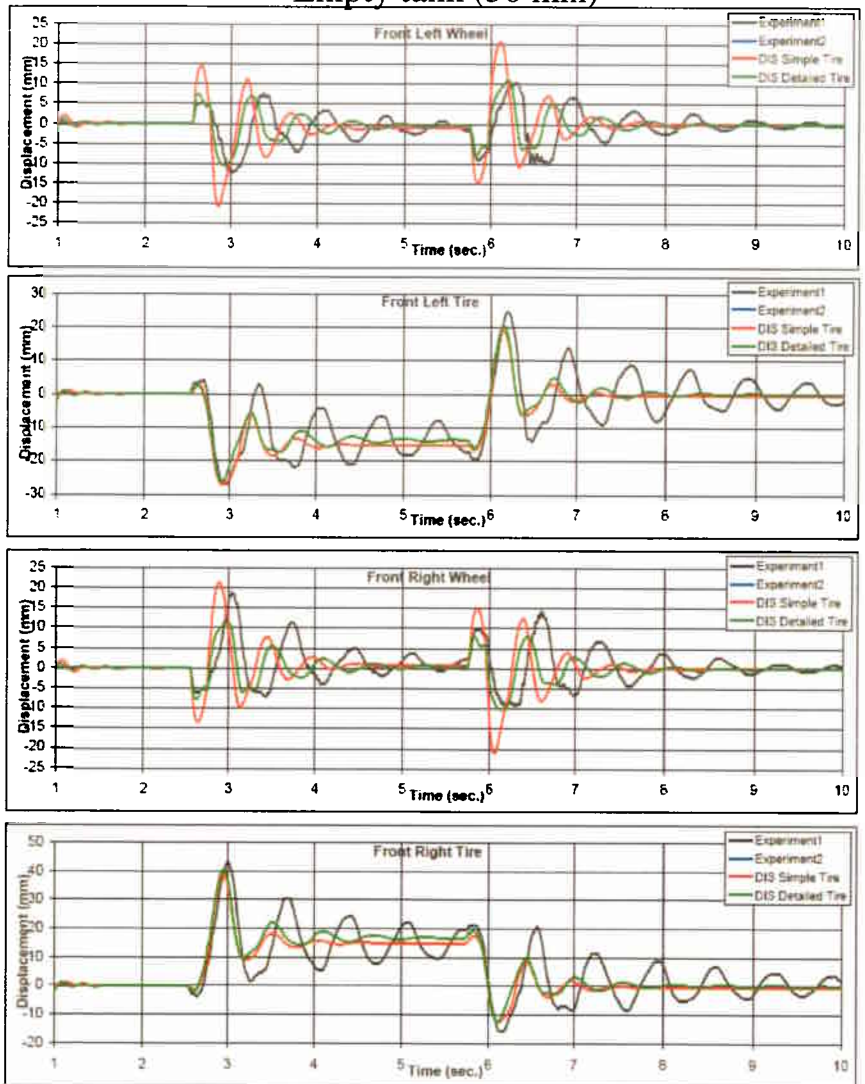
Results: roll 0.5 Hz; 48 mm harmonic excitation (cont.)



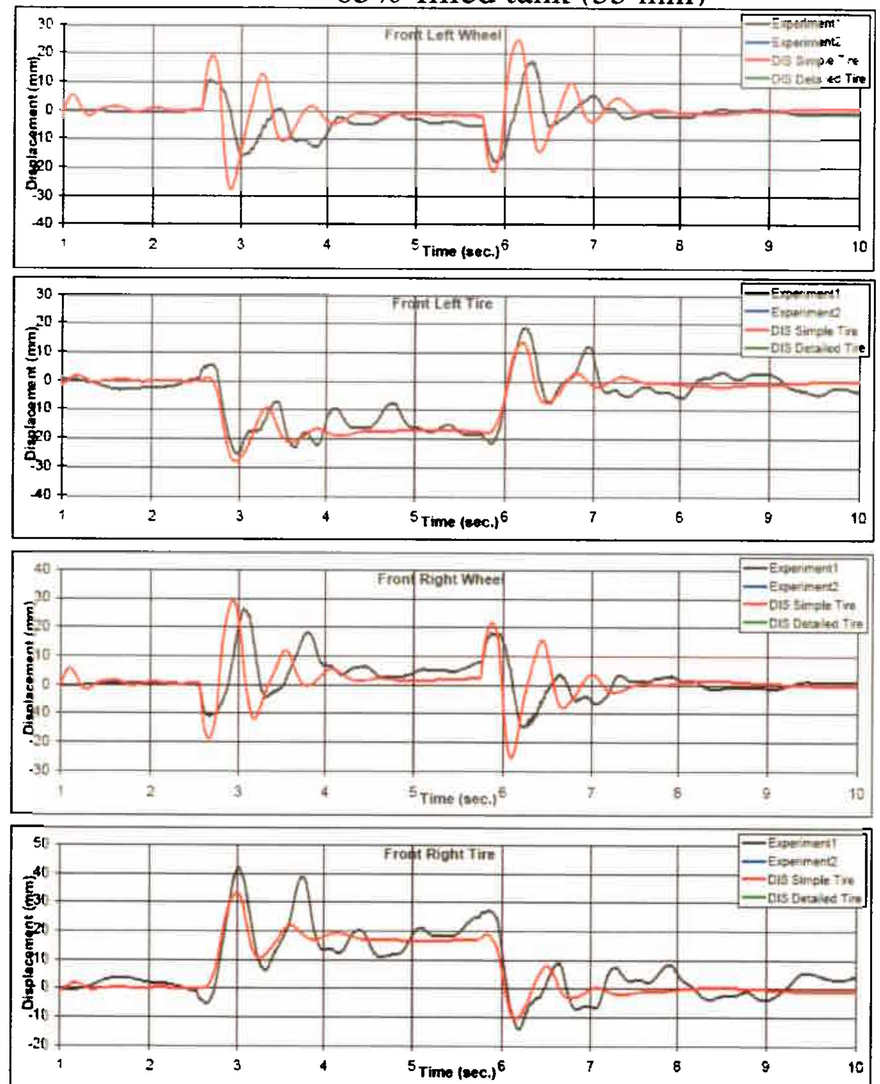
Validation Study

Results: roll 0.2 sec; 50-55 mm ramp excitation

Empty tank (50 mm)



65%-filled tank (55 mm)



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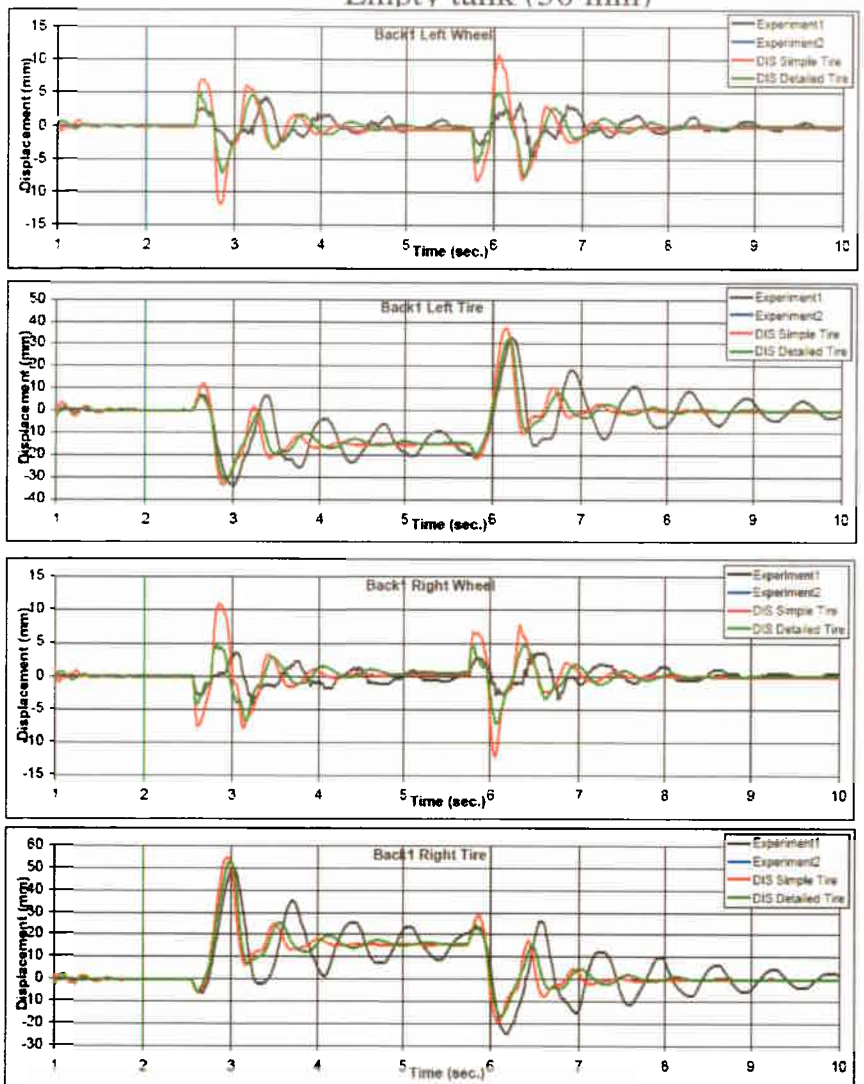
2008-01-0777

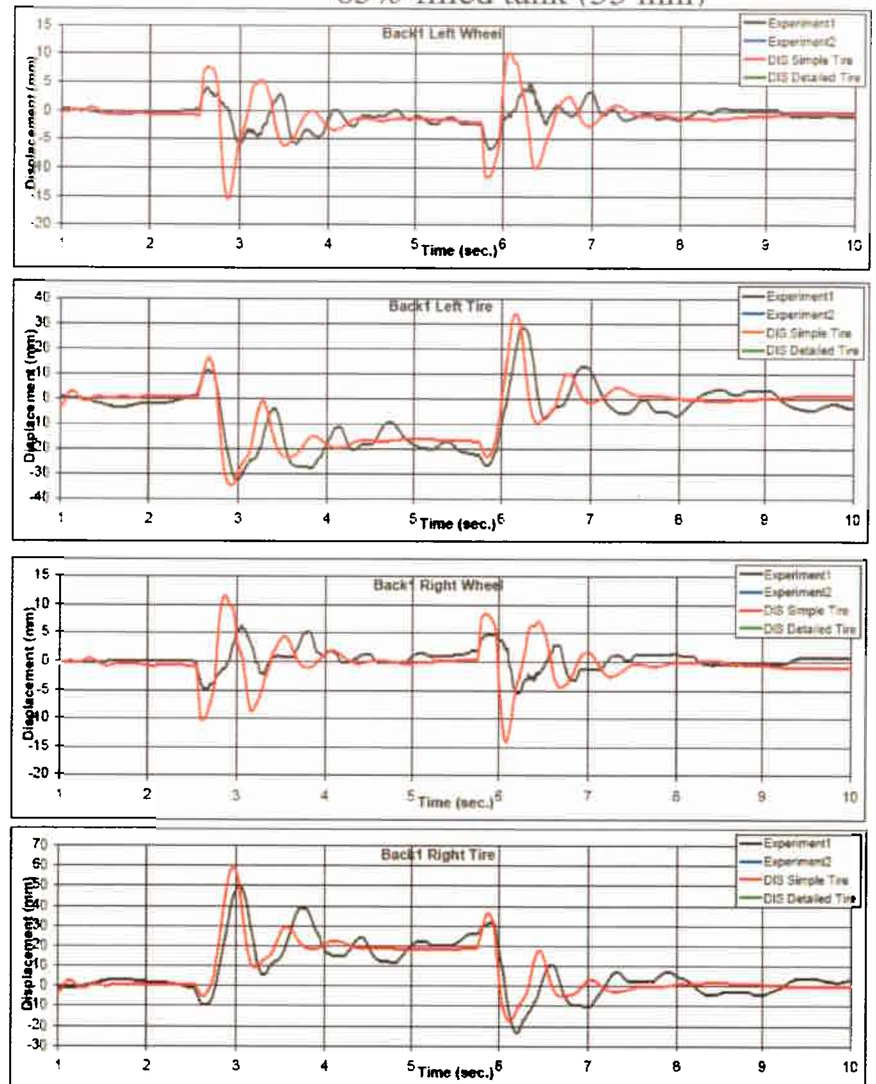
Validation Study

Results: roll 0.2 sec; 50-55 mm ramp excitation (cont.)

Empty tank (50 mm)



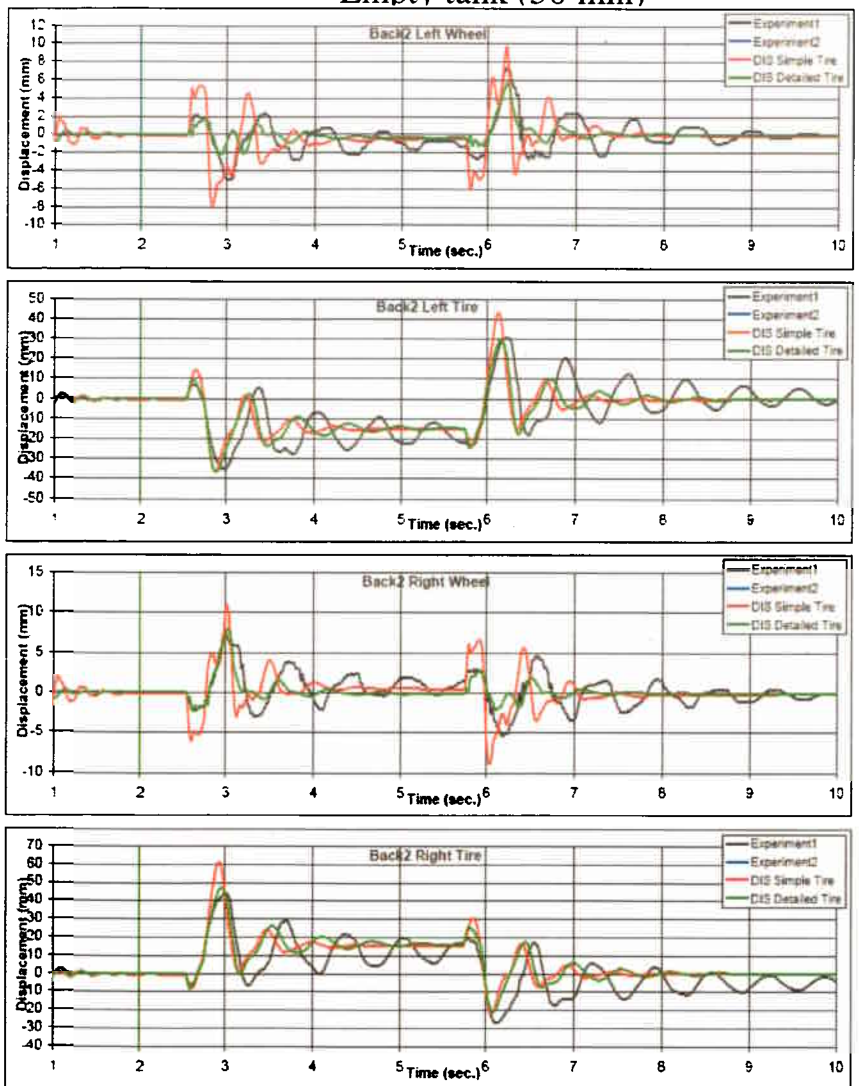
65%-filled tank (55 mm)



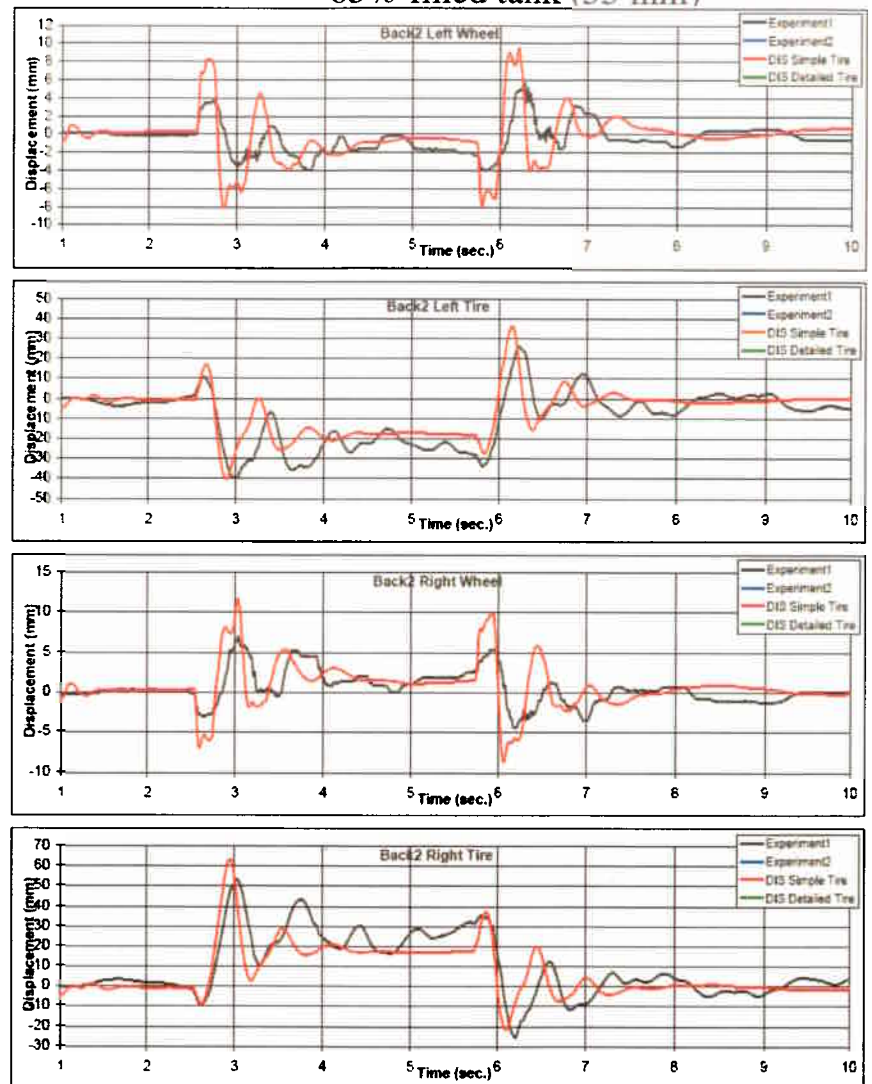
Validation Study

Results: roll 0.2 sec; 50-55 mm ramp excitation (cont.)

Empty tank (50 mm)



65%-filled tank (55 mm)



Validation Study

- Sources of experiment errors.
  - The trapezoidal dishpans at the front and back axle.
  - The tank module was not securely mounted on the trailer. There was a clearance in the connection between the Hippo and the trailer of +/- 20 mm.
  - Tire damping as a function of tire deflection was estimated.
  - Clearances in the trailer joints.
  - Non-linear behavior of the suspension leaf-springs.
  - The security harness on the tank module.

- The difference between the experiment and simulation results is about 15-20% on average.

Concluding Remarks

- A finite element model for predicting the fully coupled dynamic response of flexible multibody systems and liquid sloshing was presented. Major characteristics of the model are:
  - Explicit time-integration solver.
  - The motion of the solid and fluid is referred to a global inertial Cartesian reference frame.
  - A total Lagrangian deformation description used for the solid elements.
  - Library of accurate large rotation finite elements including: truss, beam, shell and solid elements. The elements only use Cartesian coordinates as DOFs.
  - The penalty technique is used to model contact and joints.
  - Friction is modeled using an asperity friction model.
  - The Arbitrary Lagrangian-Eulerian formulation is used to allow the fluid mesh to move/deform along with the tank.
  - VOF liquid free-surface model.
- A validation study of the finite element model was carried out using a full-scale army heavy class tactical trailer carrying a potable water tank mounted on an n-post motion simulator.
- Validation study shows that the model can predict reasonably well - within 15-20% on average - the response measured on the experiments.

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